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SELECTION OF POWER PLANT ELEMENTS FOR FUTURE REACTOR SPACE ELECTRIC POWER SYSTEMS

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ABSTRACT

We at the Los Alamos Scientific Laboratory are completing a study on the type of nuclear reactor power plants that should be developed for future space missions. With the advent of the reusable Space Transportation System , more popularly called the Space Shuttle, a new era is opening in space exploration and exploitation. The Department of Defense is especially interested in improved surveillance systems and communications. Most of these applications require power satellites at an altitude known as geosynchronous orbit - an orbit that is stationary above a fixed spot on the earth's surface. The amount of mass that a single Space Shuttle will be able to deliver to this altitude is, however, severely limited, resulting in tight restrictions for the allowable mass of candidate power supplies.

After careful consideration of power plant configuration weights, sizes, reliabilities, safety, development cost and time, we selected as the configuration to be pursued a heat-pipe reactor design, thermoelectric converters, and heat-pipe radiator.

BACKGROUND

Our studies considered various types of reactor designs, electric power conversion equipment, and reject heat systems. The designs included gas-cooled, liquid-cooled, and heat-pipe reactors. The first two have a cooling fluid directly heated by the reactor, whereas the heat pipe design uses a configuration that may be unfamiliar. Here a number of pipes are built into the reactor. A volatile fluid is sealed into the pipes. In the reactor core, the fluid is vaporized and the vapor expands through the core of the pipes. On the end which is located outside the reactor, heat is extracted by means of electrical conversion elements. This causes the vapor to condense. A wick structure located on the inside surface of the pipe provides a passage for the liquid to return to the reactor to be reheated. Thus, we achieve a self-pumping heat transfer system without incorporating fluid pumps into the power plant.

For the power converters, we considered passive types such as thermoelectrics and thermionics, and dynamic types such as a Brayton, Potassium Rankine, and Stirling cycles. The thermoelectrics take advantage of the enhanced Seebeck coefficient of semiconductor materials to convert heat to electricity. Thermionic devices use an evaporator-condensation cycle of electrons, with space charge neutralization by cesium ions, to achieve the same result. The Brayton cycle is a gas system that depends on a turbo-alternator-compressor to circulate the working fluid through the heat source and extract electrical energy. The potassium Rankine is much like a conventional, earth-based power plant where potassium is substituted for steam and operates as a liquid-vapor system. The Stirling cycle is a transient gas cycle designed to increase the cycle efficiency.

For all the above conversion systems, heat must be removed at the low side of the operating temperature interval. In space this must be done by the radiation of thermal energy. Various types of radiators were considered, including heat pipes for heat transfer and radiating surface, pumped fluid for heat transfer with fins as the radiating surface, and pumped fluid for heat transfer with heat pipes as the radiating surface.

REQUIREMENTS

Working with DoD personnel, we established a list of requirements to be used as a basis for evaluating various candidate power plants. The requirements were:

1) Power Output. Electrical power requirements in geosynchronous orbit cover the range from 10-100 kW_e for potential DoD missions.

2) Lifetimes. Lifetimes, established by anticipated developments in other components in the spacecraft, are set at seven years.

3) Reliability. The reliability design goal for the power generation unit is 0.95. Designs that avoid single failure points and degrade gradually are favored.

4) Mass. For a spacecraft requiring two Space Shuttle launches to place the entire spacecraft in orbit, the goal is 1910 kg. This is based on a three-stage Interim Upper Stage (IUS) to geosynchronous orbit and applying the general rule-of-thumb that the power subassembly can constitute up to 30% of total spacecraft mass.

5) Configuration Constraints. The Space Shuttle bay confines the spacecraft to 18.3 m length and 4.5 m diameter. The 18.3-m overall orbiter bay is reduced 7 m by the three stage IUS.

6) Radiation. The power plant must be able to operate in natural radiation fields. Induced radiation created by nuclear power systems must be reduced to the maximum acceptable radiation level under which spacecraft components can function. For present electronic components, it is 10^{13} nvt and 10^{7} rad over the mission life.

7) Maneuverability. Maneuverability is mission dependent. No missions requiring special maneuverability have been studied to date.

8) Safety Features. The power subassembly must meet all regulations of NASA, DoD, DOE, and the National Range Commanders. Space Transportation System safety policy required that the basic payload design assure the elimination or control of any hazard to the Orbiter, crew, or other payloads.

REACTOR DESIGNS

The mission requirements for high power, small size and long lifetimes imply the need for a fast spectrum, highly enriched reactor that will have a large inventory of fuel in a small volume. The large fuel inventory prevents large reactivity decreases due to fuel burnup. In seven yr, a 1-MW$_t$ reactor will burn approximately 2.5 kg of ^{235}U. This amount of burned fuel cannot represent more than a few percent of the total fuel inventory in order to maintain reactor criticality during the mission.

The reactor concepts under consideration all involve the use of refractory nuclear fuels UC-ZrC or UO_2-Mo. (UN was eliminated from core design analysis because it required nitrogen over pressure at the temperatures of interest.) Of primary importance to the power plant design is that these fuels have high uranium densities and that they allow consideration of source temperatures for electrical conversion systems up to 1400-1500 K with possible growth to 1700 K. (This requirement eliminated consideration of the hydride fuels.)

Calculations were performed on heat-pipe-cooled and gas-cooled reactors. Liquid-cooled reactors were considered using data from the SNAP-50 program.

A typical 1200-kW$_t$ heat-pipe reactor is shown in Fig. 1. The reactor core consists of a large number of heat pipes (around 90) surrounded by fuel (perhaps UO_2-2C vol% Mo). The heat pipes transfer the reactor-generated energy to the electric power conversion elements. The fuel is arranged in layers sandwiched between layers of molybdenum. The heat pipes are made of molybdenum and contain sodium as the heat transfer fluid. The core, with its large number of heat pipes, provides redundant, independent loops for removing heat. Loss of one heat pipe results in elevated, but acceptable, temperature rises in the surrounding pipes. Several failures could be sustained without major degradation of performance. This core is enclosed in a molybdenum containment vessel in order to uniformly distribute the heat on the periphery. Multifoil insulation minimizes heat transfer from the core to the reflector. Surrounding the core is a neutron reflector of beryllium on the sides and one end and BeO on the end penetrated by the heat pipes. Power control is achieved by changing the position of neutron-absorbing material within the reflector. Rotating drums containing a B_4C section are selected for reactivity control because of successful experience in previous space reactor programs. Actuators to position the control surfaces in discrete steps are placed behind the radiation shield to reduce the incident nuclear and thermal radiation. The reactor level will be controlled to maintain a constant outlet voltage from the power conversion units and to minimize thermal cycling of the reactor. Redundant instrumentation and control electronics are provided to increase reliability and eliminate single-point failures.

In the gas-cooled reactor design, gas from the converter is pumped through the reactor core. A cross-sectional view of the gas-cooled reactor is shown in Fig. 2. A pressure vessel is required for the gas-cooled reactor and inlet and outlet plenums for the working fluid. The gas-cooled reactor mates most naturally with the Brayton cycle. Typically, the working fluid is the same helium-xenon mixture that is used in the converter. An annular passage inside the pressure vessel guides the cool inlet gas from the duct attachment end to the inlet end of the core. The gas in this passage cools the pressure vessel and core periphery. Inlet and outlet ducts attach to the same end of the pressure vessel. Gas passages are required through both end reflectors. Fuel elements are hexagonal in cross section, with many small cooling holes. The fuel elements are made in short lengths. The fuel may be coated on the outside and the inside of the cooling holes to protect the gas stream against small particles spalling off.

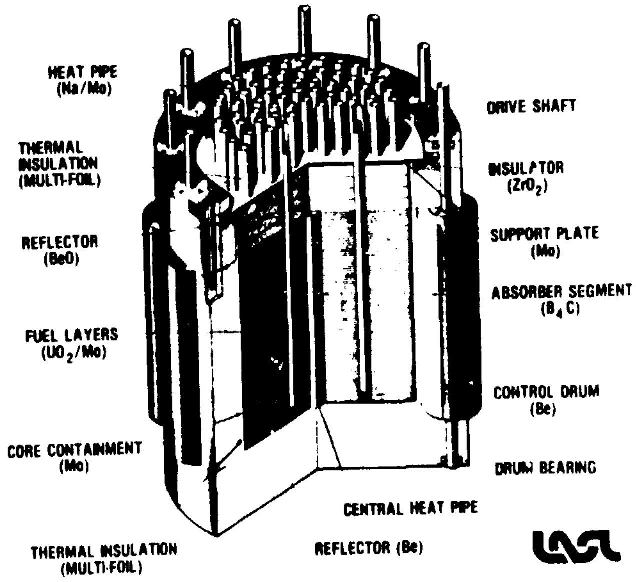

Fig. 1. Heat-pipe reactor concept.

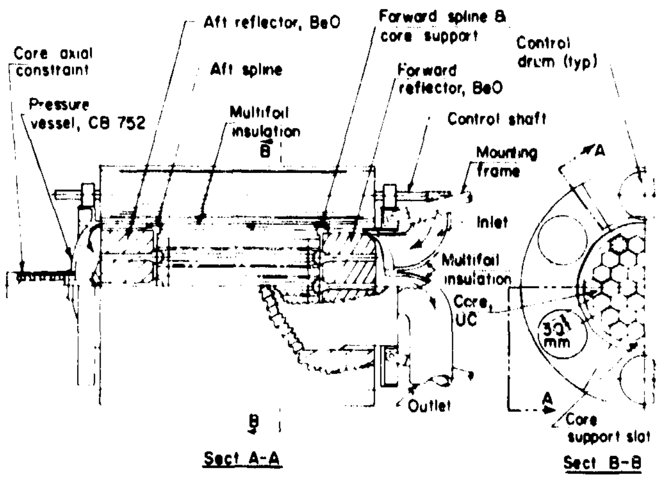

Fig. 2. Brayton-cycle gas-cooled reactor.

With regard to the liquid-metal-cooled reactor, an extensive theoretical design and experimental study was performed in the SNAP-50 Program with a potassium Rankine converter system. This activity in the 1960s has been used as the basis for our analysis. The SNAP-50 power plan contained a compact, fast spectrum reactor as the nuclear heat source. Referring to Fig. 3, heat is removed from the reactor and transported to the potassium boiler by molten lithium, which is circulated through the reactor and over the boiler tubes by a high-temperature pump. The lithium from the reactor is delivered to the boiler at a temperature around 1400 K. The shield is basically the same as the shields for the heat-pipe cooled reactor and the gas-cooled reactor. The shield is separated from the reactor to provide space for the lithium pipes to spread out from the reactor. The control drives are mounted on the other side of the shield from the reactor, with penetrations through the shield for the drive shafts. The Rankine-cycle machinery is not shown, but it is located behind the shield away from the reactor. The control of this reactor is by movable reflector segments, which function by varying the neutron leakage. This control means is particularly applicable to small, fast reactors. The segments are shown in Fig. 3 in the extended position, where reactivity would be minimum. The reflector segments are made of small BeO blocks held together by the metal canning. Fuel element assemblies consist of hexagonal cans with fuel pins stacked loosely inside. The fuel pins are composed of metal tubes, separated from each other by spiral wire wrap, and containing UC or UN ceramic fuel pellets. Each assembly is orificed to control the lithium flow rate. The assemblies are held together by circumferential straps. The lithium flow path is similar to the gas flow path in the gas-cooled reactor previously described - the coolant enters and leaves at the same end of the reactor. After entering, the coolant flows around the periphery of the core, cooling the periphery and the pressure vessel. A preheat jacket is needed to melt the coolant before operation of the reactor and the liquid metal flow system. The liquid-metal cooled reactor also required a barrier of W-25Re between the fuel and the clad. A void space is included in the fuel element assemblies for the fission gas. A comparison of heat pipe and fluid-cooled (gas or liquid) reactors indicates that one would expect similar core diameters and lengths, reflector thickness and U-235, mass because the neutronic parameters are similar. Fluid-cooled reactors do require a fluid containment or pressure vessel so they tend to be slightly heavier than heat-pipe reactors. Fig. 4 compares operating temperatures. The temperatures were taken to correspond with Brayton inlet temperatures of 1325 and 1500 K. The heat-pipe design is slightly less massive than the gas-cooled design.

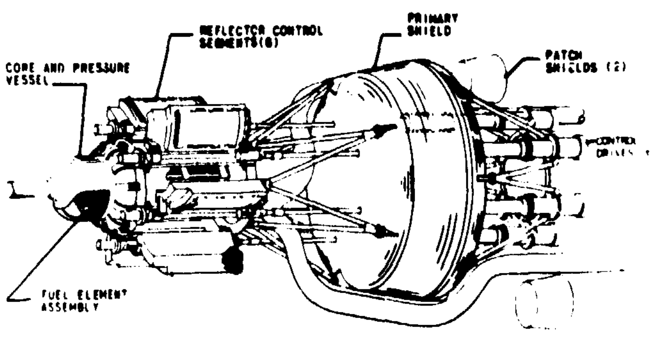

Fig. 3. Liquid-cooled reactor and shield.

The major problems with fluid reactors are that they are subject to loss of operation from a single possible failure (a fluid leak would result in termination of power operation); the core design tends to be more complex, because of the type of support structure required, fuel properties must be better known to avoid corrosion and erosion: and the reactors lack the redundancy desirable for highly reliable, long-life power plants.

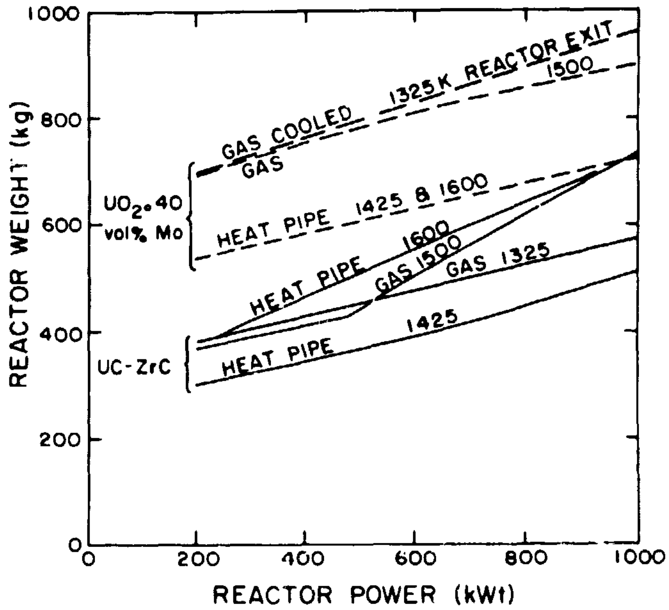

Fig. 4. Comparison of reactor weights for heat-pipe and gas-cooled reactors.

Single-failure points in fluid reactors can exist from fluid leakage either out of the pressure vessel or fluid lines, or internal failures that would result in excessive flow in certain channels and a reduction of flow in others. Either way, excessive temperatures can occur in the core and result in a power plant shutdown. Also, fuel element corrosion or erosion can lead to loss of reactivity and premature shutdown as a result of fuel swelling, embrittlement, chemical reactions with impurities in the fluid, and fluid flow forces. Heat-pipe reactors, on the other hand, have no flowing fluid in the sense of a fluid-cooled reactor. The heat pipe acts as an individual pressure containment vessel and provides a high degree of redundancy to the design by providing a large number (90) of completely independent fluid coolant channels. The heat pipes tend to be quite strong compared to the fuel claddings in fluid reactors, and, thus, heat pipe reactors can accept greater amounts of fuel swelling, cracking and embrittlement. The fuel is confined to its immediate vicinity and, thus, potential loss of reactivity due to coolant transport of fuel is minimized. Also, heat-pipe reactors have a small volume of fluid compared to fluid-cooled reactors. Problems associated with coolant activation are thereby greatly reduced.

Fluid-cooled designs are complicated by the need to control the flow into many parallel channels. This is usually done by orificing the fluid as it enters the core. Also, support structures, that have proven to be quite complex, usually in the form of plates, are needed to provide for acceleration loads, thermal expansion, and to support the fuel elements. These complications are not present in the heat-pipe reactor design.

Fuel properties must be better known in a fluid-cooled core design because rupture of the fuel clad can be disastrous to the mission. In the heat-pipe reactor, the fuel is confined outside the heat pipe allowing fluel migration without adversely affecting reactor performance. Thus, quality control for fluid-cooled reactors is more stringent and the conditions that can lead to fuel corrosion must be well established.

The lack of redundancy in a fluid-cooled reactor has already been mentioned. The lifetime and reliability goals for the reactor will therefore be much more difficult and costly to achieve. Heat-pipe reactors eliminate the need for mechanical or electromagnetic pumps. These are complex development items and difficult to operate 7 yr without maintenance.

As regards fuel considerations, a comparison of dimensions and masses for the prime fuel candidates are shown in Table I. The more-dense UC fuel results in a more compact reactor and one with lower mass. However, there are certain difficulties with the UC fuel. A major design problem exists in maintaining good thermal bonds between the fuel and the heat pipe for 7 y and also good thermal bonds between adjoining fuel modules. The thermal expansion properties of the UC-ZrC fuel and molybdenum heat pipes are quite different. Also, fuel swelling appears to be a limitation on UC, though some data indicates that alloying UC with ZrC reduces this problem. Chemical stability is also much more of a problem, with temperatures limited to below 2125 K as compared to the UO_2 limit of 2625 K. The consequences of heat pipe failures are quite sensitive to this temperature limit. Fabrication methods for UC are much less developed than UO_2. Fabrication would need to be done in a glove box environment. The major disadvantage of UO_2-Mo is the lower uranium density, as reflected in the higher reactor mass shown in Table I.

CONVERTER SYSTEM DESIGN

A. Performance. Thermoelectric and thermionic converters are passive by nature - that is, there are no mechanical moving parts. Essentially, they are built up using multiples of small modules until the desired power output is achieved. Thus, scaling the power output between 10 to 100 kW_e is achieved in a straightforward manner. Dynamic systems, on the other hand, require new hardware for each power level even though the basic design is not changed. This can lead to additional fabrication difficulties and result in higher costs.

Thermoelectrics tend to be low efficiency systems - currently 6% with the potential for twice this in the next few years. Thermionics are expected to have a system efficiency of 15-20%, but not demonstrable until 1985. Dynamic converters tend to be relatively high-efficiency devices: Brayton at 25%, Rankine at 19%, and Stirling at 30%. A comparison of efficiencies as a function of input and reject-heat temperatures (Fig. 5) indicates that Brayton-cycle efficiency decreases quickly as the reject-heat temperature increases, whereas the Stirling cycle tends to retain relatively high efficiency at the higher heat rejection temperatures. The Rankine cycle is between the two. The Brayton cycle is the only dynamic converter that can realistically be considered sufficiently developed for early 1980's power-plant design.

Reject-heat radiator area requirements are a function of converter efficiency, but more importantly, a function of reject heat temperature. Thermoelectrics operate with a radiator temperature around 775 K, thermionics at 925 K, Brayton cycle around 475 K, potassium-Rankine cycle around 800 K, and Stirling around 700 K. Radiator temperatures below 700 K tend to lead to bulky radiators that must be folded to fit into the Space Shuttle. This leads to definite design and shuttle storage complexities with the Brayton cycle.

Dynamic converters introduce vibration and torque modes into the spacecraft. These are absent from passive electrical power conversion systems.

Table II provides a list of relative weights for the various converters. It is seen that thermionics

TABLE I
COMPARISON UC AND UO_2 FUELS
(1000-kW_t Design)

SYSTEM	FUEL: UC-10 at% ZrC	UO_2-40 vol% Mo	UO_2-20 vol% Mo
Reactor mass (kg)	415	610	475
Reactor diameter (M)	0.51	0.58	0.53
U-235 (kg)	108	130	100
Shield (same converter)		20% heavier	5% heavier
FUEL FABRICATION			
Handling	Inert atmosphere	No special problems	No special problems
Fabrication method			
Current	Arc melting	Press, sinter & machine	Press, heat treat & machine
Future	Extrusion & reaction sintering	Same	Same
DESIGN			
Fuel swelling (%) (Heat pipe temp 1400 K)	8	0.1	3
Mo-fuel compatibility			
Thermal	Mismatched	Compatible	Compatible
Chemical	Interactions start at 1475 K	None up to 1975 K	None up to 1975 K
TECHNOLOGY	Less developed (Rover, LMFBR)	Well developed (LWR, LMFBR)	Well developed (LWR, LMFBR)

is potentially the lowest weight converter and Stirling cycles are currently estimated as the highest weight (a significant amount of the Stirling mass is in the linear alternator).

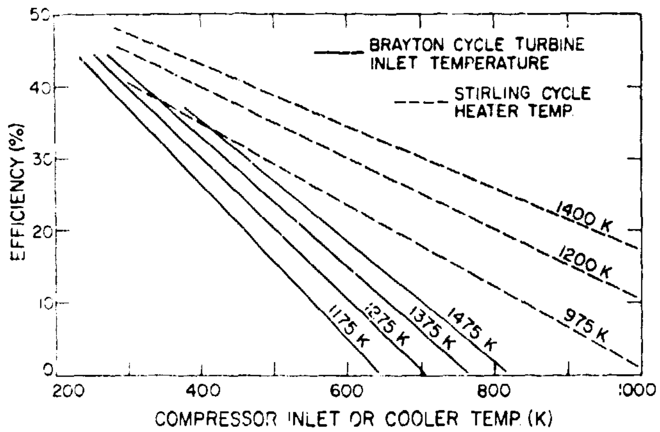

Fig. 5. Comparison of Brayton- and Stirling-cycle efficiencies.

TABLE II
RELATIVE SPECIFIC WEIGHTS OF CONVERSION UNITS
(100-kW_e Base)

	Specific Weight (kg/kW_e)
Thermoelectrics	5.[a]
Thermionics	2.[b]
Brayton cycle	7.[c]
Rankine cycle	10.[d]
Stirling cycle	12.[e]

[a]Assumes 6.4% efficiency plus cold juntion converter ring.
[b]Assumes 15% efficiency.
[c]Two-unit Brayton for redundancy.
[d]Based on redundant potassium Rankine units.
[e]Based on three 50-kW_e Stirling engines.

Thermoelectric features include:
- the best short-term candidates for up to 50 kW_e with SiGe thermoelectrics and up to 100 kW_e with SiGe-GaP thermoelectrics;
- well developed and proven Si-Ge semiconductor materials;
- proven conversion reliability;
- compression module with a high probability of success;
- efficiency of 6% almost guaranteed and high efficiency with advanced materials very probable;
- interface to heat-pipe-cooled reactor conceptually clean;
- built-in redundancy allows gradual degradation; and
- specific mass estimated at 5. kg/kW_e with Si-Ge and less with improved materials.

Thermionics features include:
- principles demonstrated with system demonstration planned by 1985;
- efficiency of 15-20% projected;
- required high reactor temperatures, like 1675 K;
- specific mass estimated at 2 kg/kW_e;
- interface with heat-pipe reactor conceptually clean; and
- built-in redundancy provides gradual degradation.

Brayton cycle features include:
- rotating machinery well developed and demonstrated;
- requires large radiator;
- efficiency of 25% at 1275 K turbine inlet, 425 K compressor inlet;
- two-converter loops needed to eliminate single-failure points and for reliability;
- problems associated with bearings, heat exchanger design, and radiator design; and
- specific mass estimated at 10 kg/kW_e at 50 kW_e, and 7 kg/kW_e at 100 kW_e levels in a dual-converter system configuration.

Rankine cycle features include:
- potassium Rankine cycle has good thermodynamic characteristics (organic-Rankine is temperature limited - not a viable candidate);
- high heat-rejection temperature;
- experience with potassium as a working fluid is good;
- turbine and cycle is complex;
- turbine, boiler, and condenser demonstrated as components, but considerable development remains, especially at system level;
- interesting only at high power where development and complexity is justified; and
- no current development programs.

Stirling cycle features include:
- Beale free-piston may meet reliability and lifetime requirement (Phillips engine rejected on basis of mechanical requirement for lubrication and seals);
- small engine under test;
- specific mass of 12 kg/kW_e with 3 half-power engines at 100 kW_e;
- mass dominated by alternator (low velocity); and
- efficiency of 30% at 1400 K heater, 700 K cooler.

B. Development. The most straightforward development activity would be thermoelectrics with SiGe. This is taken as a base for estimating the relative development effort required with each type of converter. Figure 6 shows the near-term candidates for an early 1980's ground demonstration power plant (GDS), while Fig. 7 indicates the candidates for a late 1980's GDS. The numbers in Figs. 6 and 7 indicate an estimate of the relative expense of developing various types of converters. Near-term candidates are mainly thermoelectric including SiGe, SiGe-GaP and maybe some advanced thermoelectric material and Brayton cycle with superalloy or refractory metals.

For far-term systems, although progress in achieving high thermionic efficiency has been disappointing, this system is still considered competitive with higher temperature thermoelectrics as the leading candidate.

There are possibly 135 design combinations considered in our assessment. This is without even considering all the variations in design such as different temperature Brayt n cycles and variations in thermoelectric materials.

Our choice for further design and development is:

1. Heat-pipe reactor design regardless of electrical power converter. Its advantages are:
   - the inherent high reliability from redundancy in the design;
   - the elimination of single-failure points;
   - the ability to accept material swelling, radiation damage and other environmental effects without loss of power;

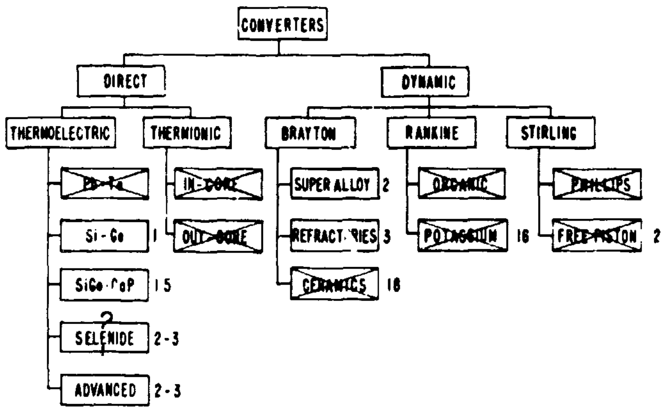

Fig. 6. Near-time converter options.

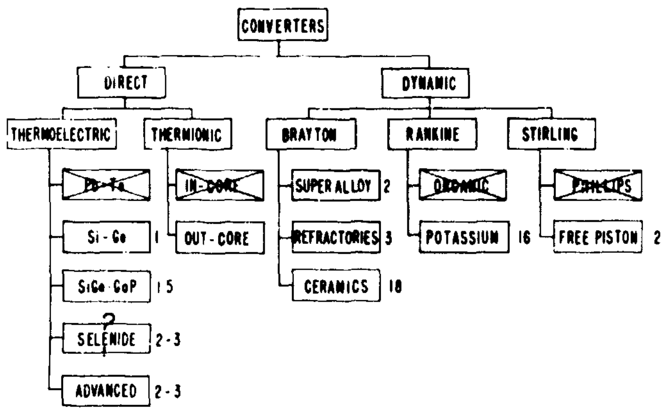

Fig. 7. Far-term converter options.

- the elimination of a need for a pressure vessel or mechanical pumps;
- the minimization of development cost because of the modular nature of the configuration; and
- the reduced susceptability to fuel erosion and corrosion deterioration.

2. Core heat pipe development should concentrate on molybdenum. Its advantages are:
   - fabrication experience exists;
   - demonstrated long-term operation for many thousands of hours at temperatures of interest, and;
   - relatively light weight.
3. Power conversion will be by thermoelectric modules. The advantages are:
   - meets the mass goal established for the power plant;
   - inherent redundancy in the design;
   - modularity provides the capability to supply different power levels without redesign;
   - relatively low development cost; and
   - extensive experience exists from the radioisotope generators to have a high degree of confidence in a successful development program.
4. Fuel development will emphasize UO_2-20 vol% material. Its advantages are:
   - minimizes overall program cost at a reasonable near-term weight penalty;
   - provides better compatibility than other fuel materials between the heat pipe and fuel materials;
   - provides more highly developed fabrication processes; and
   - can be processed in air.
5. The radiator configuration is a heat pipe design using beryllium as the prime material candidate. Its advantages are:
   - light weight;
   - high reliability;
   - redundancy without single failure points; and
   - elimination of the need for pumps.

Considering overall power plant design, we reached the following conclusions:

Our choice of a reactor design temperature depends mainly on the converter element. To minimize power plant mass and size, a temperature of around 1400 K is needed. However, to accommodate anticipated future improvements in converters, the ability to operate at several hundred degrees higher temperature should require a minimum of new development.

We selected a standard reactor design for all power levels in order to significantly save on development cost and time. When we compared a standard reactor to customized reactor designs, we found some penalty to the power that can be provided to a Single Shuttle spacecraft - peak power is reduced from 53 to 42 kW_e with a 1 MW_t standard design, to 35 kW_e with a 1.1 MW_t standard reactor, and to 23 kW_e with a 1.5 MW_t standard reactor. Peak power for dual Shuttle spacecraft exceeds 100 kW_e.

Our analysis showed that the best packaging means for various power plant configurations in the Shuttle bay depends on the particular spacecraft. We found that the radiator dominates the power plant packaging arrangement. It can be packaged in cylindrical, conical, or multiple panel arrangements. Comparing 50-kW_e power plant configurations having conical-shaped radiators and the radiator located behind the radiation shield (Fig. 8), the thermoelectric power plant would be about 6.4 m long, the thermionics power plant 3.3 m long, Brayton 10 m, potassium Rankine 3.8 m, and Stirling 4.5 m long. The Brayton requires a foldable concept for storage within the spacecraft and flexible lines between radiator segments.

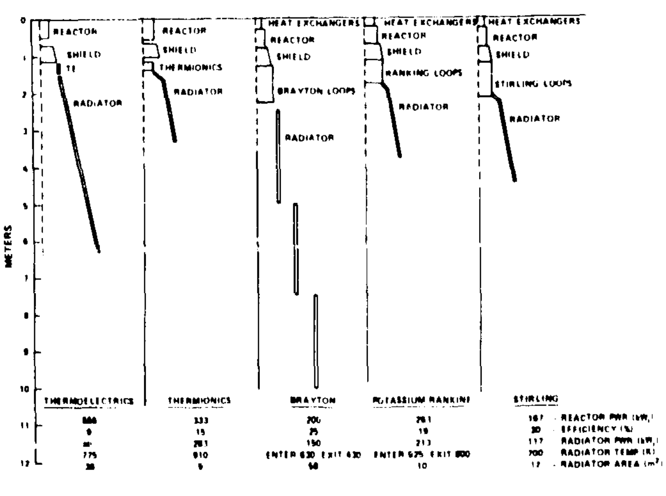

Fig. 8. Power plant size comparison at 50 kW_e.

A mass comparison is shown in Fig. 9. Thermionics and thermoelectric power plants provide some design margin to meet the mass goal established.

Our single-point failure analysis indicates that a heat-pipe reactor with thermoelectric power conversion has inherent to its design the avoidance of single failure points. If Brayton converters are us d with a heat-pipe reactor, dual converter loops can be used to eliminate single failure points. However, whis will require the addition of accumulators or other means for regulation of pressure in the two loops between half and full power. If we substitute a gas-cooled reactor for the hear-pipe reactor, we find that we can also eliminate single failure points by adding dual Brayton converters. However, a matrix of 16 valves is needed for loop isolation with these values in the inlet and outlet of the reactor. This means high temperature and large-flow-area valves leading to additional complex development items. Turning to liquid-cooled power plant designs, we found that they require a significantly more complex design arrangement to eliminate single failure points. In fact, a single failure point from one core corrosion with lithium cannot be eliminated. Again, a matrix of 16 high-temperature valves will be needed around the reactor for isolation of redundant flow loops.

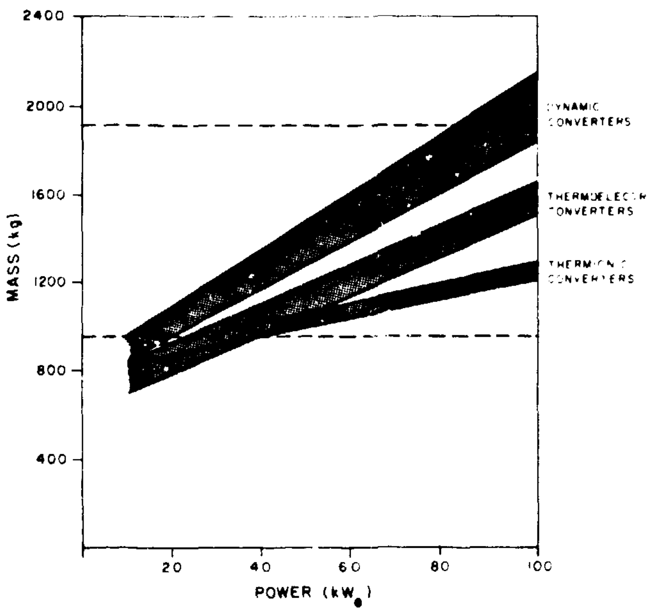

Fig. 9. Power plant weight comparison.

Our assessment of development risk, growth potential, development cost and cost benefit, indicates that the development risks for a UO_2-fueled reactor are less than UC. even for UO_2 operating at 100 K higher temperature than UC. We found that UO_2 fuel is easier to manufacture, presents fewer swelling design problems, and chemically interacts less with the molybdenum heat pipes. Growth potential is greater with UO_2-fueled reactors. However, development risk on thermoelectric material is greater with a UO_2 than UC-fueled reactor design. Higher converter efficiencies are needed to offset the higher weight of the reactor.

We performed a cost benefit analysis based on a future demand of 20 power plants as a power source for satellites in geosynchronous orbit. Our estimates for some twenty units include nuclear power plant development costs of \$150 M and production and delivery cost of \$280 M, for a total of \$430 M. This compares to some \$1260 M (excluding development costs) to provide the power with solar arrays with batteries, a savings of \$830 M.

We found that combined cycles, even though more efficient, lead to heavier-weight power plants. This was based on an analysis of power plants with thermionic converters for topping and Brayton converters as the bottoming power conversion elements.

We determined that a heat-pipe reactor provides a means for emergency-cool-down in the design without large emergency cool down fluid storage systems. This can be done by the addition of fins on the end of the reactor heat pipes with power to the fin section regulated by a gas reservoir.

ACKNOWLEDGEMENT

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